Institute of Paper Science and Technology
Atlanta, Georgia

IPST Technical Paper Series Number 810

Analysis of the Effects of Basis Weight and Moisture Nonuniformity
on Yankee Dryer Performance

F.W. Ahrens and P.E. Parker

July 1999

Submitted to
1999 TAPPI Engineering/Process & Product Quality Conference
September 12-16
Anaheim, California

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
PURPOSE AND MISSIONS

The Institute of Paper Science and Technology is an independent graduate school, research organization, and information center for science and technology mainly concerned with manufacture and uses of pulp, paper, paperboard, and other forest products and byproducts. Established in 1929, the Institute provides research and information services to the wood, fiber, and allied industries in a unique partnership between education and business. The Institute is supported by 52 North American companies. The purpose of the Institute is fulfilled through four missions, which are:

- to provide a multidisciplinary education to students who advance the science and technology of the industry and who rise into leadership positions within the industry;
- to conduct and foster research that creates knowledge to satisfy the technological needs of the industry;
- to serve as a key global resource for the acquisition, assessment, and dissemination of industry information, providing critically important information to decision-makers at all levels of the industry; and
- to aggressively seek out technological opportunities and facilitate the transfer and implementation of those technologies in collaboration with industry partners.

ACCREDITATION

The Institute of Paper Science and Technology is accredited by the Commission on Colleges of the Southern Association of Colleges and Schools to award the Master of Science and Doctor of Philosophy degrees.

ANALYSIS OF THE EFFECTS OF BASIS WEIGHT AND MOISTURE NONUNIFORMITY ON YANKEE DRYER PERFORMANCE

Frederick W. Ahrens
Professor of Engineering
Institute of Paper Science and Technology
Atlanta, GA 30318

Peter E. Parker
Associate Professor
Dept. of Paper and Printing Science and Engineering
Western Michigan University
Kalamazoo, MI 49008

ABSTRACT

A detailed computer model of the drying process on a Yankee dryer is used to investigate the effect of ingoing moisture or basis weight nonuniformity on the paper web final (crepe blade) moisture nonuniformity and maximum temperature. Specific examples are used to provide a quantitative indication of the potential productivity (Yankee speed) and uniformity benefits of flattening the profiles.

INTRODUCTION

The productivity of dryer limited paper machines is widely recognized as being connected to the water load. This implies that basis weight, sheet solids level after the press section, and final solids level (reel moisture) will all influence machine speed and productivity. It is also widely recognized that CD variability in basis weight and solids level entering the dryer section can result in wet and/or over-dried streaks at the reel, leading to the need to slow down the machine and accept a loss in productivity. Furthermore, the nonuniformity at the reel can cause a loss in product quality.

The purpose of the work presented here is to demonstrate an approach for quantifying the impact of nonuniform ingoing solids and basis weight on speed and final sheet nonuniformity. A further objective is to present example results that illustrate the expected magnitude of the speed loss and the final condition of the sheet after drying. The specific application considered is the conventional tissue/towel machine with a Yankee dryer and hot air impingement hood, in which the web is pressed onto the Yankee at a nominal solids content of about 40 to 45% and removed (by creping) at about 94 to 95% solids.

The key to the approach is the utilization of a detailed, state-of-the-art computer model of the drying process to provide the needed response data. This allows isolation/evaluation of the effect of specific, known nonuniformities and operating strategies, a luxury that is unavailable in the usual mill environment. In the examples to be presented, two situations are examined: 1) basis weight nonuniformity but uniform ingoing sheet dryness, and 2) basis weight uniformity but nonuniform ingoing dryness. The case of dryer limited operation (i.e., fixed hood temperatures and steam pressure) is assumed. The analysis is performed using the computer model to predict the drying histories of representative sheet regions, having differing basis weight or initial solids, as they proceed around the Yankee. The individual region and weighted-average crepe blade solids levels are determined as a function of Yankee speed. The predicted speed results are compared with those for drying a uniform sheet. Another parameter, the peak sheet temperature, is also evaluated as part of the analysis, since one would expect lightweight or initially drier regions to have greater temperature excursions (overdrying).

APPROACH

Two state-of-the-art computer models of the Yankee dryer have recently been developed [1], and could be considered for use in the present study. The more complete one goes beyond the scope of other published Yankee dryer models [2-4] by explicitly accounting for the heating and cooling of the Yankee surface (i.e., the surface temperature variation with respect to circumferential position). The other model utilizes the common approximation of uniform Yankee surface temperature. As shown in Ref. 1, although the surface temperature predicted by the more detailed model can vary by about 6°C (10°F) around the circumference, the simplified Uniform Surface Temperature Model (USTM) over-predicts Yankee speed by at most about 1% (at equal crepe blade solids). Thus, the USTM was selected for use in the present study. This model uses a numerical integration of the local sheet mass and energy balance differential equations to compute the variation of moisture and temperature with circumferential position on the Yankee. Variations of temperature in the thickness direction are neglected (with support from the results of Karlsson and Heikkilä [4]). Included in the original version of the model [1] are a moisture-dependent Yankee-sheet contact heat transfer coefficient [5], a moisture and temperature-dependent hygroscopic vapor pressure reduction factor [6], and corrections of the local convective heat and mass transfer rates for finite vapor flux through the boundary layer [7,8]. Typically, one would be guided by data such as that presented by Rounds [9] in selecting the steam condensation heat transfer coefficient. The numerical solution procedure employed in the original version [1] involves an iteration process in which the differential equations are integrated along the MD direction (over the wrapped portion of the Yankee) several times, for different values of the surface temperature, until a surface temperature is found for which an overall energy balance on the Yankee is satisfied. During the solution, the Yankee speed is held constant (and, thus, the crepe blade solids level varies).

Since the publication of the original Uniform Surface Temperature Model [1], several extensions and improvements have been incorporated into the model. These are: inclusion of the Martin correlation [10] for hood air impingement heat transfer [facilitating introduction of meaningful nozzle box parameters (i.e., nozzle velocity, nozzle diameter, discharge coefficient and open area) into the model]; inclusion of a moisture-dependent latent heat increment [6] for the hygroscopic regime; and use of appropriate mass, momentum and energy balances to calculate required steam, gas and electricity usages, hood exhaust conditions and supply air flow rates and pressures. Furthermore, the iterative numerical solution procedure now includes the option of specifying the crepe blade solids (thus necessitating an iterative adjustment of Yankee speed).

For purposes of analyzing the effects of basis weight or ingoing moisture nonuniformity, it is assumed that the weight or moisture streaks do not interact. Thus, the individual streaks will have the same Yankee speed, but will, in general, have different drying rates and final solids and temperature levels.

RESULTS AND DISCUSSION

The model can be used to study a wide variety of operating conditions. Model predictions of Yankee speed should compare well with real machine speeds. The base condition for the present discussion is the set of operating parameters indicated in Table I. In the following discussion, one or more of the parameters was modified and results were predicted. Only the variables mentioned were changed; all others remain at the base condition.

The model can be used to predict the impact of changes in operating conditions on production. Figure 1 illustrates the impact of changing the desired crepe blade solids on machine speed. As expected, as the desired solids level decreases, the speed can be increased. The increase is nearly linear over much of the range of crepe blade solids, but the speed penalty increases dramatically as the desired solids increases beyond about 97%. As shown in Figure 2, a similar change holds true as the basis weight is changed. The curves in Figure 2 are for an incoming moisture of 40%, but similar curves are computable for other incoming moisture levels.

Figures 3 and 4 are similar to Figures 1 and 2, except that the effect of changing the incoming moisture level or basis weight on machine speed is illustrated. Speed is approximately linearly related to inlet sheet solids, but there is a slight curvature to the speed-basis weight relationship. At any given exit solids, the machine must slow down to accommodate the higher water loads as the incoming moisture (at constant basis weight) or the incoming basis weight (at constant moisture) increases.

Figure 5 shows that the average (TAPPI) drying rate is very dependent on the exit moisture and moderately dependent on the incoming sheet solids. At high exit solids, the decrease in overall average drying rate becomes rather significant and it is this dramatic drop in drying rate that results in a severe machine speed penalty for high dryness. These results demonstrate that the commonly used water load vs. speed relationship (constant drying rate assumption) is only an approximation. This point has been made previously [11] in connection with analysis of the conventional multicylinder dryer section. A similar phenomenon occurs with changes in the incoming basis weight (Figure 6). However, for fixed incoming sheet solids, all basis weights have the same drying rate. This is a consequence of the neglect of web internal heat and mass transfer resistances in the model. This approximation is believed to be adequate/reasonable, as the drying rate is primarily driven by moisture content (through sheet surface contact and hygroscopic effects) and temperature, and is thus relatively independent of basis weight.

As the drying rate of the increasingly dry sheets drops, the maximum temperature of the sheet begins to rise. (The maximum temperature of the sheet occurs just as the sheet leaves the hood. As it travels to the blade, it cools slightly.) As shown in Figure 7, the sheet temperature increases rapidly as the drying rate falls off. At exit solids above about 96%, the sheet temperature starts to exceed the normal boiling point of water. This is mainly a result of the water being more tightly bound to the sheet, resulting in an apparent increase in the latent heat of vaporization and a reduction in vapor pressure [6]. This phenomenon requires an increase in sheet temperature to sustain the required mass transfer from the sheet.

The model can be used to estimate the impact of nonuniformities in the incoming sheet on production. Two examples illustrate this.

Example 1. Moisture Nonuniformity

Example 1 considers a sheet having a significant moisture deviation in the CD profile. The desired incoming sheet is 21.2 g/m^2 at 40% solids. However, due to some machine upsets, 20% of the sheet width is at 39% and 20% of the sheet width is at 41% solids content. The remainder of the sheet is at the desired 40% solids content. Thus, the average incoming moisture content is at the desired level, but with significant positive and negative deviations. We ask the question --- How much must the machine speed be adjusted to achieve some desired average exit solids?

Figure 8 shows the predicted exit, or blade, solids as a function of Yankee speed for these moisture conditions. This figure is similar to Figure 1, but with a much narrower speed range. At the normal incoming moisture content, the sheet can be dried to 94% solids at a Yankee speed of about 1177 m/min (3860 fpm). However, at this speed, the wet spot (39% moisture) will still be quite wet, somewhere around 86% by extrapolating the curves in Figures 1 or 8. On the other hand, the portion of the sheet that entered at 41% would have an exiting solids content around 98% and a resulting sheet temperature around 110 °C (230 °F). This portion of the sheet is greatly overdried and there is the risk of burning and odor problems. To dry the wet spot to 94% solids requires that the machine be slowed to almost 1128 m/min (3700 fpm), resulting in significant overdrying of the remainder of the sheet.

Even though the incoming average sheet solids is 40%, the exit average solids level is not the same as if the entire sheet were at the uniform 40% incoming moisture. The average exit solids for this condition is shown via the short line just below the blade solids line for 40% moisture. This line represents the width-weighted average of the blade solids for each of the sheet sections. As a result of the different drying rates for the wet, normal, and dry portions of the sheet, the average sheet solids are slightly lower than those for the uniform moisture sheet. Thus, even to obtain the same average sheet solids as the uniform moisture sheet, the machine must be slowed. At an average solids level of about 94.5% (the upper limit of the average curve in Figure 8), this amounts to about 7.6 m/min (25 fpm) -- and the wet part of the sheet is still at about 90% solids.

A slightly less drastic deviation is shown in Figure 9. In this case, there is a wet streak of 1 percentage point in 10% of the sheet width (e.g., 39% solids) and the remainder of the sheet is at the desired 40% incoming solids. The speed penalty to dry this wet streak to 94% solids is the same as in the previous case since the drying of the wet streak controls the machine speed. The middle curve in Figure 9 is the width-weighted average of the exit solids. The speed penalty to dry the sheet to an average 95% solids requires a 7.6 m/min (25 fpm) penalty relative to drying the uniform sheet to that level. This is a similar penalty to that discussed for Figure 8, but in this case a much smaller portion of the sheet is wet and there is no compensating dry portion of the sheet.

Example 2. Basis Weight Nonuniformity

Example 2 is similar to a "smile" or "frown" in the basis weight profile. One portion of the sheet is 0.8 g/m^2 above the average basis weight and an equivalent portion is 0.8 g/m^2 below the average. As a result, the average basis weight is correct, but there are both a heavy area and a light area. Assuming no CD movement of fiber or water, it really makes no difference whether these disturbances represent single, wide steps or multiple narrow deviations. All that is critical in this analysis is that the overall average remains at the set point.

The middle line in Figure 10 represents the performance of the Yankee at the desired inlet condition of 40% solids at 21.2 g/m^2. The upper curve represents the drying of the light portion of the sheet and the lower curve represents the heavier portion of the sheet. The vertical line at about 1177 m/min (3860 fpm) shows the response of the system at the nominal operating point. The intersection with the right hand (lighter weight) curve shows that the low basis weight portion of the sheet will be dried to about 97.5% solids, with the attendant risk of burning the sheet. The heavy spot, on the other hand, will have a moisture content that is about 88% solids (by extrapolation). This wet a sheet might pick or break or lead to poor product quality. To thoroughly dry the heavy spot, the machine must be slowed to about 1135 m/min (3725 fpm), thus seriously overdrying the lighter weight portion of the sheet.

The two examples presented illustrate how the model can be used to estimate the impact of incoming sheet variations on machine speed and hence machine productivity. The excursions illustrated above may seem rather large if considered as step changes somewhere in the sheet. However, it is not unusual to find "smiles" or "frowns" in which the basis weight or moisture variation is similar to that illustrated in the examples. In addition, all the small excursions that comprise the CD variability may easily add up to 15 or 20% of the sheet width.

CONCLUSIONS

A detailed drying model can help determine the benefits of flattening a moisture or basis weight profile. In particular, application of such a model can give insight into the variation of final moisture and paper temperature associated with specified ingoing moisture and/or weight variations and operating strategies. While the results presented in Figures 1-10 are only valid for the base conditions given in Table I, they can be used as a preliminary estimate of the production benefits associated with a flattened profile.

REFERENCES

1. Ahrens, F. W., *Proceedings ASME Heat Transfer Division,* HTD-317-2, ASME, New York, 1995, p. 427.
2. Spraker, W. A., Wallis, G. B., and Yaros, B. R., *Pulp and Paper Canada*, 70(1): 55 (1969).
3. Rounds, D. A. and Wedel, G. L., *Proceedings First International Symposium on Drying*, A.S. Mujumdar, Ed., Science Press, Princeton, 1978, p. 185.
4. Karlsson, M. and Heikkilä, P., in *Drying '87*, A.S. Mujumdar, Ed., Hemisphere, Washington, 1987, p. 194.
5. Sundberg, T., Andersson, N., Löfgren, K., and Österberg, L., *Svensk Papperstidning*, 71(8): 317 (1968).
6. Prahl, J. M., "Thermodynamics of Paper Fiber and Water Mixtures," Ph.D. Thesis, Harvard University, Cambridge, Massachusetts, 1968.
7. Bird, R. B., Stewart, W. E., and Lightfoot, E. N., *Transport Phenomena*, J. Wiley & Sons, New York, 1960.
8. Lienhard, J. H., *A Heat Transfer Textbook*, 2nd Ed., Prentice-Hall, Englewood Cliffs, 1987.
9. Rounds, D. A., *Proceedings 1982 International Water Removal Symposium,* CPPA, Montreal, p. 35.
10. Martin, H., in *Advances in Heat Transfer,* Vol. 13, Academic Press, New York, 1972, p. 1.
11. Deshpande, R. D. and Pulkowski, J. H., *Proceedings 1992 Tappi Engineering Conference, Book 2,* TAPPI Press, Atlanta, p. 639.

Table I. Parameters for Yankee Model Base Condition

OD Basis Wt. on Yankee, g/m^2	21.2
Sheet Solids to Yankee, % (Base Case)	40.
Paper Temp. to Yankee, °C	27
Sheet Solids at Crepe Blade, % (Base Case)	94.
Total Sheet Wrap on Yankee, degrees	321.
Sheet-Yankee Contact Fraction (multiplier for contact parameters below)	0.9
Yankee Steam Pressure, kPa (gauge)	620
Yankee Diameter, m	4.57
Yankee Shell Thickness, cm	4.32
Shell Thermal Conductivity, W/m-°C	41.5
Yankee Coating Spray, kg/min-m	1.79
Wet End Hood Supply Temp., °C	482
Dry End Hood Supply Temp., °C	482
Wet End Supply Humidity, kg Water/kg Dry Air	0.4
Dry End Supply Humidity, kg Water/kg Dry Air	0.4
Pre-Hood Wrap Angle (press roll to hood), degree	36.
Wet End Hood Wrap Angle, degrees	128.
Dry End Hood Wrap Angle, degrees	127.
Nozzle Air Velocity, m/min	7315
Hood Open Area Fraction	0.015
Nozzle - Yankee Gap, cm	2.54
Nozzle Diameter, cm	0.79
Nozzle Discharge Coefficient	0.69
Ambient Air Temp., °C	27
Ambient Air Humidity, kg Water/kg Dry Air	0.02
Makeup Air Temp., °C	27
Makeup Air Humidity, kg Water/kg Dry Air	0.02
Pulp Type (Previously Dried Fibers)	-
Contact Heat Transfer Parameter (Intercept), W/m^2-°C [1]	199
Contact Heat Transfer Parameter (Slope), W/m^2-°C [1]	4542
Condensation Coefficient, W/m^2-°C	852
Ambient Convection Coefficient, W/m^2-°C	56.8

Figure 1

Blade Solids vs Yankee Speed
At Fixed Inlet Solids

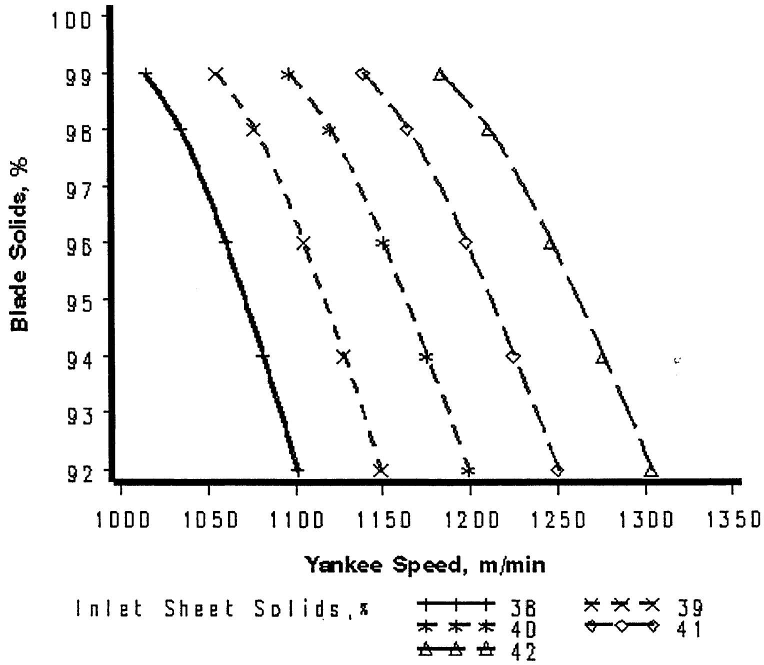

Figure 2

Exit Solids vs Yankee Speed
At Fixed Basis Wt.
(Inlet Solids = 40%)

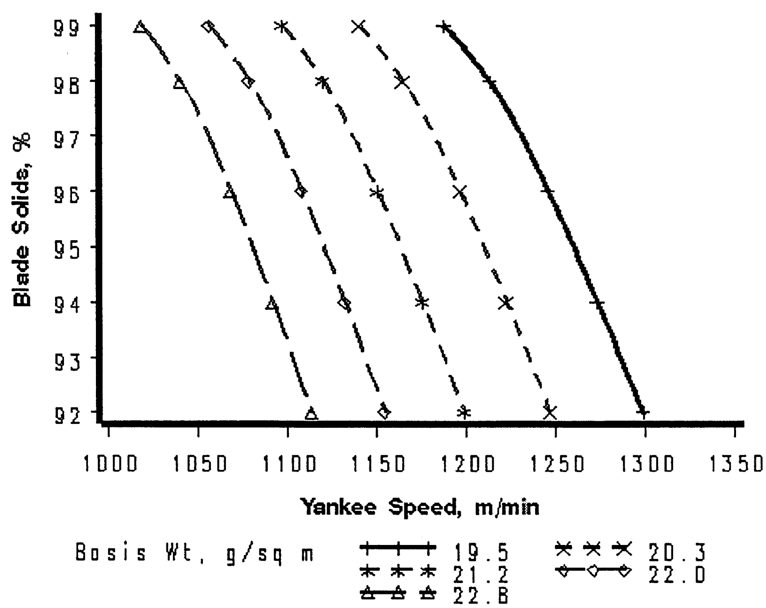

Figure 3

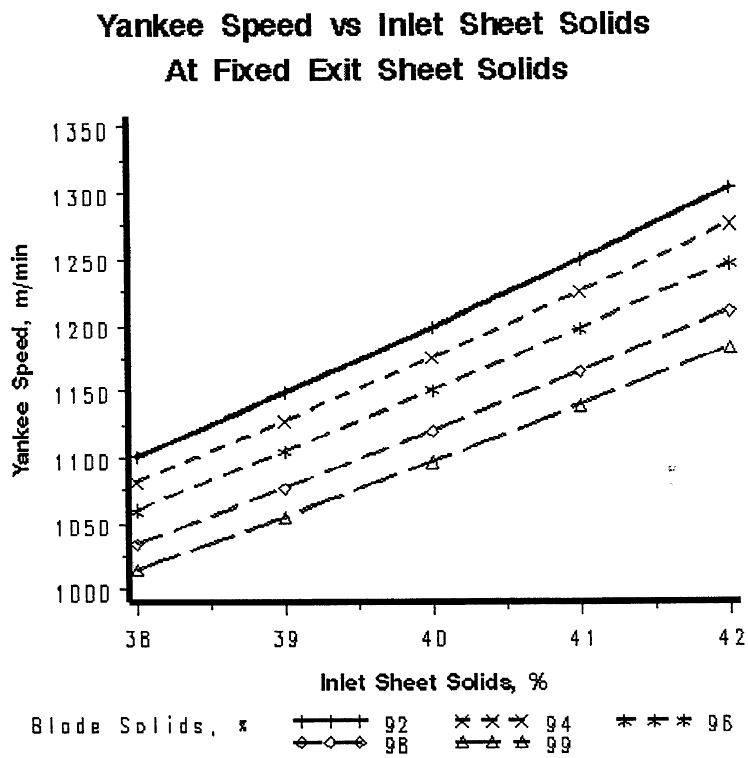

Figure 4

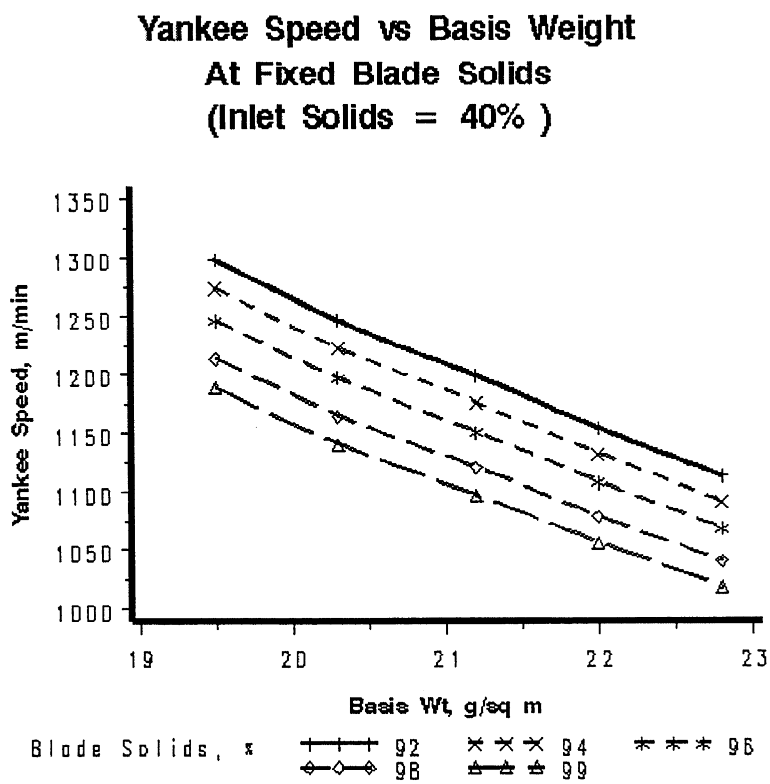

Figure 5

TAPPI Drying Rate

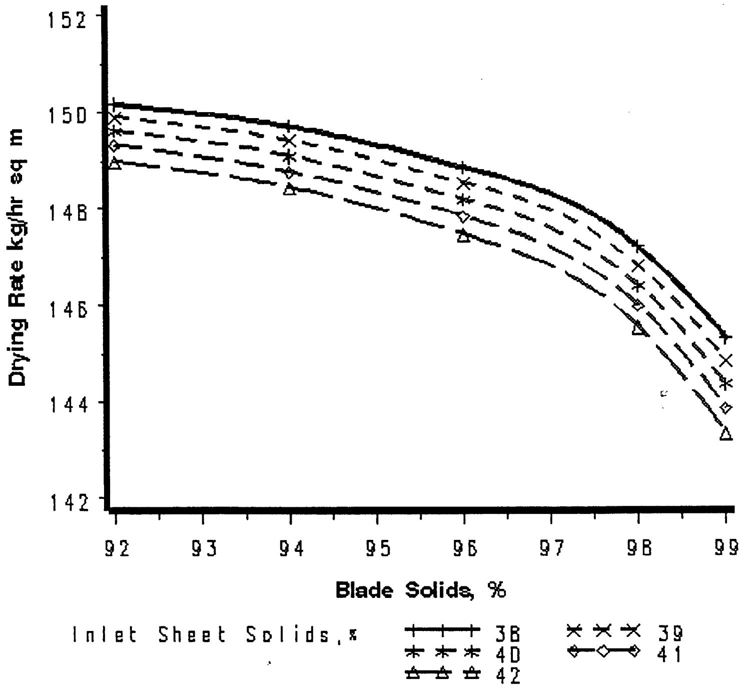

Figure 6

TAPPI Drying Rate vs Exit Solids At Fixed Basis Weight (Inlet Solids = 40%)

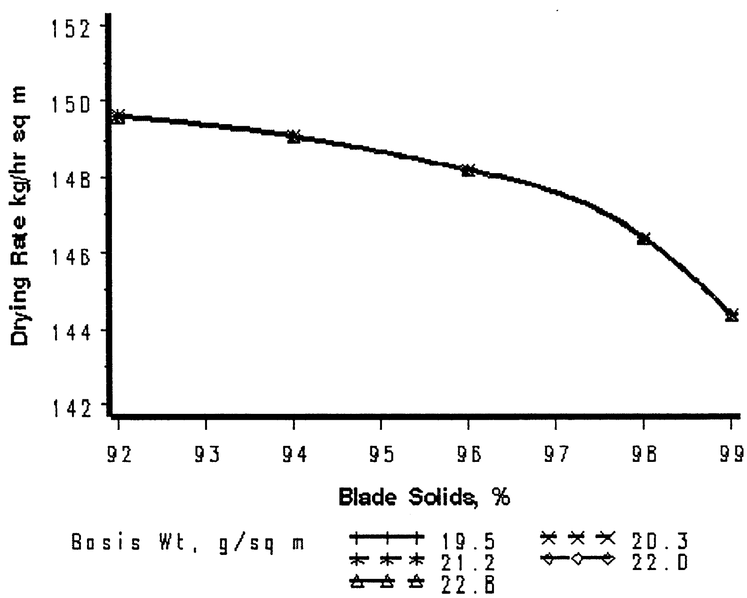

Figure 7

Maximum Sheet Temperature

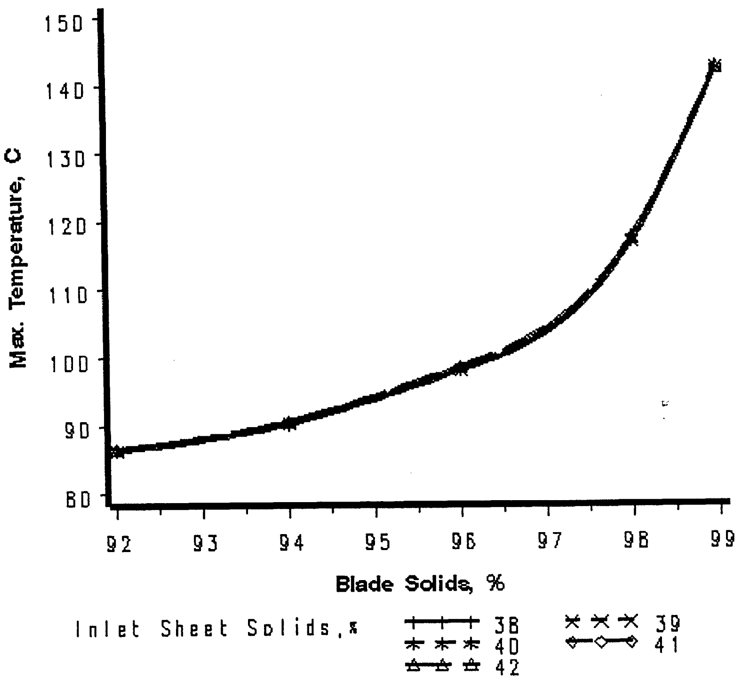

Figure 8

Impact of Moisture Variation
At Fixed Basis Wt (21.2 g/sq m)
Wet and Dry Spikes are 20% of Sheet

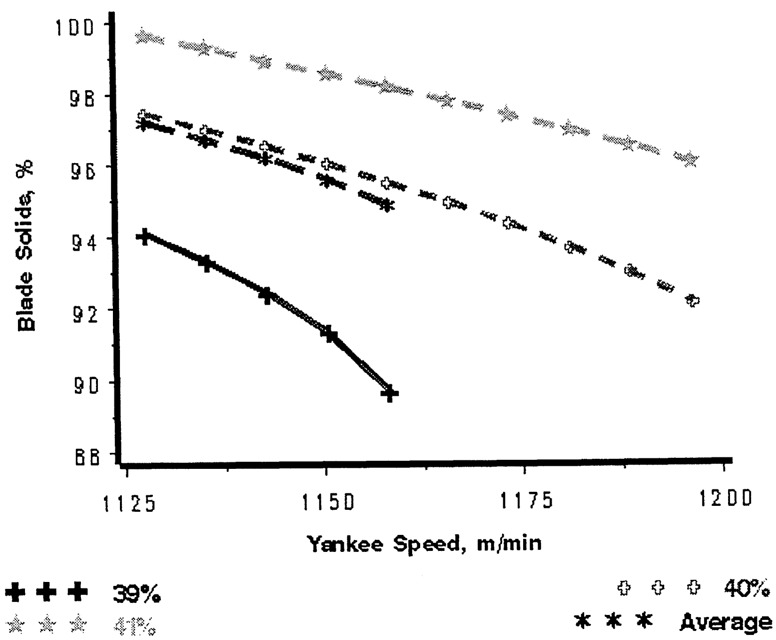

Figure 9

Impact of Moisture Variation
At Fixed Basis Wt (21.2 g/sq m)
Wet Spikes is 10% of Sheet

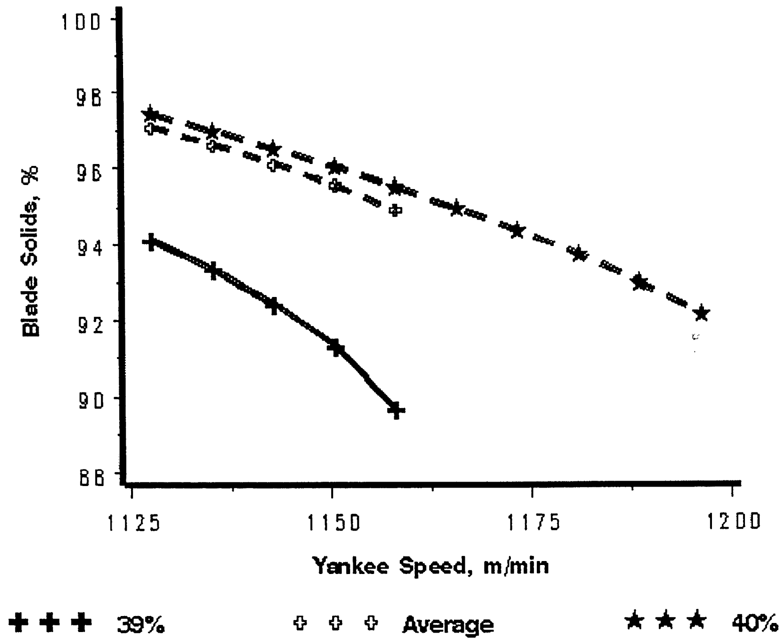

Figure 10

Impact of Basis Weight Variation
At Fixed Inlet Solids (40%)